

Constraints on R-parity violating stop couplings from flavor physics

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Abstract

We perform a critical reassessment of the constraints on the R-parity and baryon number violating (s)top couplings coming from flavor physics. In particular, we study $K^0-\bar{K}^0$ mixing, including QCD corrections and a class of diagrams that were neglected in previous analyses: both effects give sizeable contributions. We explain how the resulting bounds can be translated into constraints on individual couplings in the simplest class of flavor models, based on U(1) horizontal symmetries. We finally discuss the implications for the possibility of observing single superparticle production at the Tevatron.

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1 Introduction

In the Minimal Supersymmetric Standard Model (MSSM) it is assumed that R-parity (R_p) is conserved [1]. While the particles of the Standard Model are even under R_p , their supersymmetric partners are odd, thus the latter can only be produced in pairs and they always decay into final states involving an odd number of supersymmetric particles. Although it considerably simplifies the structure of the MSSM, the conservation of R-parity has no firm theoretical justification (for a review and references on versions of the MSSM with broken R-parity, see e.g. [2]). The most general R_p -violating superpotential that can be written with the MSSM superfields contains both lepton number and baryon number violating terms. Their simultaneous presence is in fact strongly limited, since it would induce fast proton decay. However, it is possible to allow for the presence of baryon number violating couplings only [3], coming from the superpotential

$$\mathcal{W}_{\mathcal{B}} = \lambda''_{ijk} \epsilon^{\alpha\beta\gamma} U_{i\alpha}^c D_{j\beta}^c D_{k\gamma}^c, \quad (1)$$

where U^c and D^c (c denotes charge conjugation) are the chiral superfields associated with SU(2)-singlet antiquarks, in a basis where the quark masses are diagonal, $i, j, k = 1, 2, 3$ are flavor indices and $\alpha, \beta, \gamma = 1, 2, 3$ are color indices. The color structure of $\mathcal{W}_{\mathcal{B}}$ implies that the λ''_{ijk} are antisymmetric in the last two indices, limiting the number of independent couplings to 9.

A number of recent works [4]-[8] studied the production of *single* supersymmetric particles at the Fermilab Tevatron through the R-parity and baryon number violating couplings of eq. (1) that involve a top (s)quark. These works were motivated by the consideration that, while the R_p and baryon number violating couplings λ''_{1jk} which involve an up (s)quark are severely constrained by the absence of neutron-antineutron oscillations [3, 9] and double nucleon decay into kaons [10], the limits on the couplings that involve a top (s)quark are believed to be much weaker, of order $\lambda''_{3jk} < 1$ for sfermion masses heavier than 100 GeV (see e.g. [5] and references therein). Moreover, in most scenarios of supersymmetry breaking it is reasonable to expect that the third-generation squarks are lighter than the other sfermions, due to the effect of their large Yukawa couplings on the renormalization group evolution of the masses between the ultraviolet cutoff scale of the MSSM and the weak scale. Thus, if the couplings λ''_{3jk} are not much smaller than 1, and the third-generation squarks are not too heavy, it should be possible to observe single stop production in the interaction of two down-type antiquarks, or single sbottom production in the decay of a top quark.

In view of this situation, it is extremely interesting to understand how the constraints on the R_p -violating (s)top couplings that can be derived from low-energy experimental data compare with the bound $\lambda''_{3jk} < 1$ considered in Refs. [4]-[8]. In this note we will study the constraints that can be derived from flavor physics. In particular, in section 2 we will perform a careful study of the limits coming from $K^0-\bar{K}^0$ mixing, including QCD corrections and a class of diagrams that were neglected in previous analyses [10]-

[12]: both effects give sizeable contributions. We will show that $K^0-\bar{K}^0$ mixing places an upper bound of order (few) $\times 10^{-2}$ on the combination $|\lambda''_{313}\lambda''_{323}|^{1/2}$ of R_p -violating (s)top couplings. For degenerate couplings, $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} \equiv \lambda''$, this is significantly stronger than the bounds usually considered in the literature. In section 3 we will consider a more refined way of translating the bounds coming from $K^0-\bar{K}^0$ mixing into bounds on the individual couplings λ''_{3jk} : it makes use of the simplest models of flavor, those based on U(1) horizontal symmetries, to correlate the size of the different couplings. Finally, in section 4 we will apply our analysis to the specific scenarios considered in Refs. [4]-[8], and we will show that $K^0-\bar{K}^0$ mixing strongly constrains the possibility of observing single superparticle production at the Tevatron, not only under the rough assumption of degenerate couplings, but also assuming the most general hierarchies allowed by realistic U(1) flavor symmetries.

Before addressing our main points, we comment on some bounds that were previously discussed in the literature. The R-parity and baryon number violating interactions affect, at the one-loop level, the coupling of the Z boson to the right-handed down-type quarks. The upper bounds quoted in Refs. [4]-[8] come from the measurement of $R_l \equiv \Gamma(Z \rightarrow \text{hadrons})/\Gamma(Z \rightarrow l^+l^-)$ [13]. However, in order to derive a reliable bound on the couplings λ''_{3jk} , the contributions of both R_p -violating and R_p -conserving MSSM interactions to the Z -peak observables must be taken into account [14]. A recent analysis of the whole set of hadronic Z -peak observables [15] suggested that the couplings λ''_{3j3} are ruled out at 95% confidence level. The reason is that, while the data ask for a positive shift in the coupling of the right-handed b quarks to the Z boson with respect to its Standard Model value, the λ'' corrections shift this coupling in the negative direction. However, the interpretation of these results appears to be controversial: it was shown in [15] that the bounds on λ''_{3j3} coming from the Z -peak data are much weaker if one performs a Bayesian statistical analysis instead of the classical one.

The experimental bound on neutron-antineutron oscillations was used [9] to set limits on the R_p -violating couplings λ''_{1jk} which involve an up (s)quark. In a subsequent paper [16], a similar analysis was performed on a class of diagrams that also contribute to neutron-antineutron oscillations, but allow to set limits on the couplings λ''_{3jk} . Contrary to what claimed by the authors of [16], we have found that such limits are not competitive with the ones that can be derived from flavor physics.

The authors of [11] studied the contribution of the R_p -violating terms to some rare decays of the B^+ meson, namely $B^+ \rightarrow \bar{K}^0 K^+$ and $B^+ \rightarrow \bar{K}^0 \pi^+$. In order to reduce the theoretical uncertainties, they considered the ratio of the partial width of the rare decay to the partial width of the decay $B^+ \rightarrow K^+ J/\psi$, which proceeds unsuppressed in the Standard Model. The limits on the R_p -violating couplings that can be derived in this way are less stringent than those coming from $K^0-\bar{K}^0$ mixing, but still one order of magnitude below those assumed in [4]-[8]. Using the formulae of Ref. [11], with updated values for the experimental upper bounds on the branching ratios and for the CKM matrix elements [17],

and assuming that the lightest stop mass eigenstate is approximated by \tilde{t}_R , we obtained:

$$|\lambda''_{312}\lambda''_{323}| < 3.0 \times 10^{-3} \frac{m_{\tilde{t}_R}^2}{m_W^2}, \quad |\lambda''_{312}\lambda''_{313}| < 3.9 \times 10^{-3} \frac{m_{\tilde{t}_R}^2}{m_W^2}. \quad (2)$$

As an example we can consider the representative parameter choice recently used for the discussion of single stop production at the Tevatron (see section 4 for the details concerning this scenario). In the case of degenerate couplings $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} \equiv \lambda''$, and taking into account the mixing in the stop sector, we obtained the upper limit $\lambda'' < 0.15 - 0.24$ for a light stop mass ranging between 180 and 325 GeV.

2 Improved constraints from $K^0-\bar{K}^0$ mixing

Bounds on the R_p -violating couplings can be derived from $K^0-\bar{K}^0$ mixing [10]-[12]. Flavor-changing neutral currents in SUSY models can arise in a “direct” way, when the flavor violation occurs through flavor violating vertices in the diagrams, or in an “indirect” way, due to the existence of non diagonal sfermion masses in the basis where the fermion masses are diagonal. In minimal supergravity scenarios, where the soft mass matrices at the GUT scale are flavor diagonal, non diagonal squark masses are generated by flavor violating couplings through the renormalization group equations. However, as shown in [12], their contribution to $K^0-\bar{K}^0$ mixing can be neglected. Thus, in the following we will assume that the quark and squark mass matrices are diagonalized by the same rotations.

The diagrams that give the dominant contributions to $K^0-\bar{K}^0$ mixing in minimal supergravity scenarios with R-parity violation are shown in fig. 1. The most general $\Delta S = 2$ effective Lagrangian can be written as:

$$\mathcal{L}_{\text{eff}}^{\Delta S=2} = \sum_{i=1}^5 C_i Q_i + \sum_{i=1}^3 \tilde{C}_i \tilde{Q}_i, \quad (3)$$

where the four-fermion operators Q_i and \tilde{Q}_i are defined as in [18]. The operators relevant to this analysis are $Q_1 = \bar{d}_L^\alpha \gamma_\mu s_L^\alpha \bar{d}_L^\beta \gamma^\mu s_L^\beta$ (α, β are color indices), coming from the Standard Model diagram (fig. 1a), $\tilde{Q}_1 = \bar{d}_R^\alpha \gamma_\mu s_R^\alpha \bar{d}_R^\beta \gamma^\mu s_R^\beta$, coming from the diagrams with four λ'' couplings (fig. 1b-c), and $Q_4 = \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta$, $Q_5 = \bar{d}_R^\alpha s_L^\beta \bar{d}_L^\beta s_R^\alpha$, coming from the diagrams with two CKM and two λ'' couplings (fig. 1d-e). The corresponding coefficients C_i are evaluated at a common scale M_S , where the supersymmetric particles are integrated out. We computed all the coefficients that are relevant to the case under consideration, including the contributions of charginos and charged Higgs that were neglected in earlier analyses [10]-[12]: their explicit expressions are given in the Appendix.

The contribution of the effective Lagrangian $\mathcal{L}^{\Delta S=2}$ to the K_S-K_L mass difference Δm_K is related to the matrix element $\langle K^0 | \mathcal{L}_{\text{eff}}^{\Delta S=2} | \bar{K}^0 \rangle$. The coefficients C_i must be evolved from the scale M_S , which is of order of the masses of the supersymmetric particles, down to some hadronic scale μ_h (e.g. 2 GeV) at which the matrix element can be evaluated. Moreover,

the long-distance hadronic processes give contributions to the matrix elements $\langle K^0 | Q_i | \bar{K}^0 \rangle$ that cannot be evaluated perturbatively, and are parametrized by “bag factors” B_i (for the explicit definitions see [18]). We have calculated the contribution of the R_p -violating couplings to Δm_K , using the NLO QCD evolution of the coefficients C_i and the lattice calculations for the B_i presented in [18]. It is interesting to note that the main effect of the QCD corrections, which were neglected in earlier analyses, is a sizeable enhancement of the coefficient C_4 .

Due to the large uncertainties that affect the theoretical evaluation of Δm_K in the Standard Model (see e.g. [19] and references therein), a conservative limit on the R_p -violating couplings can be derived by requiring that the contribution to Δm_K of the diagrams shown in fig. 1b-e is not larger than the experimental value $\Delta m_K^{\text{exp}} = (3.489 \pm 0.008) \times 10^{-15}$ GeV [17]. When all the contributions of the diagrams shown in fig. 1b-e are taken into account, the resulting limit on the product $\lambda''_{313} \lambda''_{323}^*$ depends in a nontrivial way on the spectrum of sparticle masses and mixing angles. As a first step, we derived an upper bound on the R_p -violating couplings by performing a general scan over the parameter space of the MSSM at the weak scale. According to the standard lore on the hierarchy problem, we varied the soft squark masses m_{Q_3} , m_{U_3} and m_{D_3} , the gaugino mass M_2 and the charged Higgs mass m_{H^+} between 100 GeV and 1 TeV, the squark trilinear couplings A_t , A_b and the μ parameter between -1 TeV and 1 TeV, and $\tan \beta$ between 1 and 50, with the constraint that the mass spectrum of superpartners is not already excluded by direct searches. The result is that, for any choice of the MSSM parameters, the upper limit on the R_p -violating couplings is of order $|\lambda''_{313} \lambda''_{323}^*|^{1/2} < 0.033$ or lower (the weakest bound is obtained when m_{U_3} , m_{D_3} and $|\mu|$ get their maximal value). This is significantly stronger than the upper limit $|\lambda''_{313} \lambda''_{323}^*|^{1/2} < 0.12$ quoted in [11] for the case $m_{\tilde{b}_R} = 1$ TeV, $m_{\tilde{t}_R} = 900$ GeV. However, the authors of [11] neglected in their analysis the contribution of the diagram with chargino exchange shown in fig. 1e, as well as the effect of squark mixing and QCD corrections.

3 Constraints from flavor symmetries

As noticed above, flavor changing processes allow to set bounds only on products of two different λ''_{3jk} couplings. To discuss the implications for single superparticle production at colliders, however, it would be interesting to translate these bounds into bounds on the individual couplings. Two extreme but simple-minded choices that are often made in the literature consist in assuming either degenerate couplings or only one non-vanishing coupling: in the first case, $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} \equiv \lambda''$, the limit from K^0 – \bar{K}^0 mixing is simply $\lambda'' < 0.033$ or lower, whereas in the second case the only non-vanishing coupling is unconstrained. However, none of these two choices is natural, as can be easily realized considering flavor models based on horizontal symmetries. As a representative case we shall concentrate here on the class of models based on a U(1) flavor symmetry, but similar

considerations could be made for all other realistic flavor models. In abelian flavor models, the Yukawa couplings for up-type and down-type quarks are of order $Y_{ij}^U \sim \epsilon^{h_2+q_i+u_j}$ and $Y_{ij}^D \sim \epsilon^{h_1+q_i+d_j}$ respectively, while the R-parity and baryon number violating couplings are of order $\lambda_{ijk}'' \sim \epsilon^{u_i+d_j+d_k}$, where $\epsilon \sim 0.2$ is a parameter of the order of the Cabibbo angle and h_i, q_i, u_i and d_i denote the charges of the corresponding MSSM superfields (in the basis of interaction eigenstates) under the additional U(1) symmetry. It has been shown [20]-[22] that the correct pattern of quark masses and mixing angles can be reproduced only with the following two sets of charge assignments:

$$(I) \quad (q_{13}, q_{23}) = (3, 2), \quad (u_{13}, u_{23}) = (5, 2), \quad (d_{13}, d_{23}) = (1, 0), \quad (4)$$

$$(II) \quad (q_{13}, q_{23}) = (-3, 2), \quad (u_{13}, u_{23}) = (11, 2), \quad (d_{13}, d_{23}) = (7, 0) \quad (5)$$

where $q_{ij} \equiv q_i - q_j$ etc. In the basis of interaction eigenstates, the hierarchy among the λ_{3jk}'' couplings follows the pattern:

$$\lambda_{312}'' \approx \lambda_{313}'' \approx \kappa \lambda_{323}'', \quad (6)$$

where $\kappa = \epsilon$ in case I (i.e. a mild hierarchy) and $\kappa = \epsilon^7$ in case II (a strong hierarchy). However, the hierarchy is attenuated in the basis of eq. (1), where the quarks are mass eigenstates. Following Refs. [23, 20, 21] the quark mixing matrices can be evaluated at leading order in ϵ upon diagonalization of the Yukawa matrices. We found that in the basis of quark mass eigenstates the hierarchy among the λ_{3jk}'' couplings follows the pattern of eq. (6), with $\kappa = \epsilon$ in case I and $\kappa = \epsilon^3$ in case II. In the presence of such hierarchy, the upper limit on the unsuppressed coupling λ_{323}'' coming from K^0 - \bar{K}^0 mixing is rescaled by a factor of $\kappa^{-1/2}$ with respect to the case of degenerate couplings, while the upper limit on the suppressed couplings λ_{312}'' and λ_{313}'' is rescaled by a factor of $\kappa^{1/2}$: the resulting bounds are $\lambda_{323}'' < 0.07$, $\lambda_{312}'' \approx \lambda_{313}'' < 0.015$ in case I and $\lambda_{323}'' < 0.37$, $\lambda_{312}'' \approx \lambda_{313}'' < 0.003$ in case II. Thus, even in the less stringent situation, the upper bound on the largest R-parity violating (s)top coupling is at most of order (few) $\times 10^{-1}$, i.e. one order of magnitude below the bounds assumed in Refs. [4]-[8].

4 Implications for single superparticle production

We are now ready to discuss the implications of our results for single superparticle production at colliders. In [4] the production of single top squarks via R_p violation in $p\bar{p}$ collisions at the Tevatron was studied. If some of the couplings λ_{3jk}'' are greater than 10^{-2} or so, the rate for the production of a single light stop \tilde{t}_1 in $p\bar{p}$ collisions at $\sqrt{S} = 2$ TeV may exceed the rate for stop-antistop pair production, due to the greater phase space available. Thus, R_p violation could be the favorite scenario for the observation of supersymmetric particles at the Tevatron. The authors of [4] considered a supergravity-inspired scenario, where at the Grand Unified Theory (GUT) scale the common gaugino mass is $m_{1/2} = 150$ GeV, the scalar trilinear coupling is $A_0 = -300$ GeV and the common scalar mass m_0 is varied

in a range between 50 and 500 GeV. The ratio of the Higgs vacuum expectation values is chosen to be $\tan\beta = 4$ and the Higgs mass parameter μ , whose absolute value is fixed by electroweak symmetry breaking, is chosen to be positive. The three R_p -violating (s)top couplings were taken to be degenerate, $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} \equiv \lambda''$. The signal coming from single stop production in $p\bar{p}$ collisions, followed by the R_p -conserving decay $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+$, with $\tilde{\chi}_1^+ \rightarrow l + \nu + \tilde{\chi}_1^0$, was considered in [4] together with the Standard Model background. The conclusion was that, for $180 < m_{\tilde{t}_1} < 325$ GeV and $\lambda'' > 0.02 - 0.06$, it should be possible to discover the top squark at run II of the Tevatron, otherwise the limit on the R_p -violating couplings could be lowered to $\lambda'' < 0.01 - 0.03$ at 95% confidence level. Moreover, existing data from run I should allow for a reduction of the limit to $\lambda'' < 0.03 - 0.2$ for $180 < m_{\tilde{t}_1} < 280$ GeV. We computed the upper bound on λ'' coming from $K^0 - \bar{K}^0$ mixing in the minimal supergravity scenario considered by the authors of [4], for the same choice of parameters. The resulting limits are of order $\lambda'' < 0.015 - 0.020$ for a light stop mass ranging between 180 and 325 GeV, as shown in fig. 2. In the same figure, the limits resulting from the general scan over the MSSM parameters described above are shown, and it can be seen that they never exceed $\lambda'' < 0.033$. The (weaker) limits coming from rare decays of the B^+ boson (see section 1) are also shown. In summary, under the assumption of degenerate R_p -violating (s)top couplings, the discovery of single stop production via R-parity violation at the Tevatron turns out to be unlikely.

In the presence of a hierarchy among the couplings such as that of eq. (6), suggested by U(1) flavor models, the lower limit for single stop discovery on the unsuppressed coupling λ''_{323} must be rescaled by a factor of $(0.95\kappa^2 + 0.05)^{-1/2}$ with respect to the case of degenerate couplings, taking into account that the relative contribution of λ''_{323} to the total cross section $p\bar{p} \rightarrow \tilde{t}_1$ is roughly 5%. On the other side, as discussed in section 3, the upper limit on λ''_{323} coming from $K^0 - \bar{K}^0$ mixing is rescaled by a factor of $\kappa^{-1/2}$. In case I ($\kappa = \epsilon$) the upper limit from $K^0 - \bar{K}^0$ mixing becomes $\lambda''_{323} < 0.034 - 0.045$, while the lower limit for single stop discovery becomes $\lambda''_{323} > 0.07 - 0.20$: no room for single stop discovery at the Tevatron is left. In case II ($\kappa = \epsilon^3$) the upper limit from $K^0 - \bar{K}^0$ mixing becomes $\lambda''_{323} < 0.17 - 0.22$, while the lower limit for single stop discovery becomes $\lambda''_{323} > 0.09 - 0.27$. Although single stop discovery at the Tevatron cannot be excluded in this case, most of the parameter space considered in [4] is ruled out.

A very similar discussion can be made concerning the results of [7], where the production of single gluinos at hadron colliders, $p\bar{p} (pp) \rightarrow \tilde{t}\tilde{g} (t\tilde{g})$, was studied. Such process occurs through the exchange of a virtual squark, produced in the R-parity violating interaction between two quarks. The authors of [7] considered a supergravity-inspired scenario where at the GUT scale $m_0 = 1$ TeV, $A_0 = -1$ TeV, $\tan\beta = 10$, $\mu > 0$ and $m_{1/2}$ is varied between 120 and 400 GeV, i.e. a region of the parameter space where the squarks are heavier than the gluino (with the possible exception of the light stop). The R_p -violating stop couplings were taken to be degenerate, $\lambda''_{3jk} \equiv \lambda''$. The conclusion was that, if the gluino is lighter than 400 GeV and λ'' is of order 1, it will be possible to detect single gluino production at the Run II of the Tevatron. At the LHC the process can potentially

be seen with the gluino lighter than 1 TeV and λ'' of order 0.01. We computed the upper bound on λ'' coming from $K^0-\bar{K}^0$ mixing, with the choice of parameters considered in [7]. The result is that $\lambda'' < 0.028 - 0.035$ for a gluino mass ranging between 350 GeV and 1 TeV. Thus, under the assumption of degenerate λ''_{3jk} couplings, the discovery of single gluino production at the Tevatron is unlikely, while room is left for discovering the same process at the LHC. The same conclusion holds in the presence of a moderate hierarchy among the couplings, such as the one suggested by the U(1) flavor models of section 3.

In [8] the decay $t \rightarrow \bar{b} \bar{d} \tilde{\chi}_1^0$ was studied. If the light sbottom has a non-negligible right-handed component, the top quark may undergo the R_p -violating decay $t \rightarrow \tilde{b}_1 \bar{d}$ through the coupling λ''_{313} , followed by the R_p -conserving decay $\tilde{b}_1 \rightarrow \bar{b} \tilde{\chi}_1^0$. The authors of [8] considered a scenario where at the weak scale $\mu = -200$ GeV, $\tan\beta = 1$ and $M_2 = 100$ GeV. With this choice of the parameters the masses of the lightest chargino and neutralino are $m_{\tilde{\chi}_1^\pm} = 120$ GeV and $m_{\tilde{\chi}_1^0} = 55$ GeV, respectively. The conclusion of [8] was that, if the sbottom \tilde{b}_1 is lighter than 160 GeV and¹ $\lambda''_{313} > 0.5$, it will be possible to observe the R_p -violating top decay at the Run II of the Tevatron, while the observation at the LHC will be possible for $\lambda''_{313} > 0.1$. The same conclusion holds for the decay $t \rightarrow \bar{b} \bar{s} \tilde{\chi}_1^0$, driven by the R_p -violating coupling λ''_{323} . We computed the upper limits on the combination $|\lambda''_{313}\lambda''_{323}|^{1/2}$, using for M_2 , μ and $\tan\beta$ the same values as in [8], and varying the other MSSM parameters in the way described in section 2. The results are shown in fig. 3 as a function of the right sbottom mass $m_{\tilde{b}_R}$ (with our choice of μ and $\tan\beta$ the mixing in the sbottom sector is negligible). It can be noticed that, when the right sbottom is lighter than 160 GeV, the upper bounds on the R_p -violating couplings are of order $|\lambda''_{313}\lambda''_{323}|^{1/2} < 0.013$ or lower. Thus we conclude that, if the couplings λ''_{313} and λ''_{323} are degenerate (or if there is a hierarchy between the couplings such as the one suggested by U(1) flavor models), the discovery of R_p -violating top decays is unlikely. In any case, we cannot expect to observe both the decays $t \rightarrow \bar{b} \bar{d} \tilde{\chi}_1^0$ and $t \rightarrow \bar{b} \bar{s} \tilde{\chi}_1^0$.

5 Conclusions

In summary, we have improved the existing bounds on the R_p -violating couplings λ''_{3jk} , showing that they are typically more stringent than those assumed in [4]-[8]. For the bounds coming from $K^0-\bar{K}^0$ mixing we have included QCD corrections and a class of diagrams that were neglected in earlier analyses [10]-[12]: both effects give sizeable contributions. We have discussed a way of translating the resulting bounds into constraints on the individual couplings, making use of the simplest class of flavor models based on U(1) horizontal symmetries. Finally, we have shown that our bounds put severe constraints on the possibility of observing single superparticle production via R-parity violation at the Tevatron.

¹Our normalization of the couplings λ''_{ijk} (eq. 1) differs by a factor of 2 from the one used in [8].

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Appendix

We have calculated the contributions to $K^0-\bar{K}^0$ mixing coming from the full set of diagrams with R_p -violating (s)top couplings λ''_{3jk} . In particular, the contribution of the diagram in fig. 1e, which was neglected in earlier analyses [10]-[12], turns out to be sizeable. The calculation has been performed in the basis where the quark masses are diagonal, and all the flavor changing squark mass insertions have been neglected. We have also checked that in the scenarios considered in [4]-[8] the contributions coming from the R-parity conserving sector of the MSSM (i.e. from diagrams with quarks and charged Higgs or squarks and charginos in the internal lines) are negligible. The coefficients C_i that appear in eq. (3) are:

$$C_1 = \sum_{i,j=1}^3 \frac{g^4}{128\pi^2} K_{i1}^* K_{i2} K_{j1}^* K_{j2} m_{u_i}^2 m_{u_j}^2 \left[I_0 + 2 I_2/m_W^2 + I_4/4 m_W^4 \right] (m_{u_i}^2, m_{u_j}^2, m_W^2, m_W^2) \quad (7)$$

$$\tilde{C}_1 = \sum_{i,j=1}^2 \frac{1}{4\pi^2} |\lambda''_{313} \lambda''_{323}|^2 \left[(O_{i2}^t O_{j2}^t)^2 I_4(m_b^2, m_b^2, m_{t_i}^2, m_{t_j}^2) + (O_{i2}^b O_{j2}^b)^2 I_4(m_{b_i}^2, m_{b_j}^2, m_t^2, m_t^2) \right] \quad (8)$$

$$\begin{aligned} C_5 = & \sum_{i=1}^2 \frac{g^2}{4\pi^2} \lambda''_{313} \lambda''_{323} (O_{i2}^b)^2 K_{31}^* K_{32} m_t^2 \left[I_2(m_{b_i}^2, m_W^2, m_t^2, m_t^2) + \right. \\ & \left. \frac{1}{4 m_W^2} I_4(m_{b_i}^2, m_W^2, m_t^2, m_t^2) + \frac{1}{4 m_W^2 \tan^2 \beta} I_4(m_{b_i}^2, m_{H^+}^2, m_t^2, m_t^2) \right] \\ & + \sum_{i,j,k=1}^2 \frac{g^2}{8\pi^2} \lambda''_{313} \lambda''_{323} O_{j2}^t O_{k2}^t K_{31}^* K_{32} \left[V_{i1}^* O_{j1}^t - \frac{m_t}{\sqrt{2} m_W \sin \beta} V_{i2}^* O_{j2}^t \right] \times \\ & \left[V_{i1} O_{k1}^t - \frac{m_t}{\sqrt{2} m_W \sin \beta} V_{i2} O_{k2}^t \right] I_4(m_b^2, m_{\tilde{\chi}_i^+}^2, m_{t_j}^2, m_{t_k}^2) \end{aligned} \quad (9)$$

and $C_4 = -C_5$. In the above equations, K_{ij} are the CKM matrix elements, O_{ij}^t and O_{ij}^b are the left-right mixing matrices of the stop and sbottom sectors, and V_{ij} is the mixing matrix of positive charginos as defined in [24]. The functions I_n result from integration over the Euclidean momentum \bar{k} of the four particles circulating in the loop:

$$I_n(m_1^2, m_2^2, m_3^2, m_4^2) = \int_0^\infty \frac{\bar{k}^n d\bar{k}^2}{(\bar{k}^2 + m_1^2)(\bar{k}^2 + m_2^2)(\bar{k}^2 + m_3^2)(\bar{k}^2 + m_4^2)} \quad (10)$$

In the numerical study of the minimal supergravity scenario, the masses of the supersymmetric particles and the mixing angles at the weak scale have been calculated with ISAJET

[25], and the common scale M_S has been chosen as the geometrical mean of squark and chargino masses.

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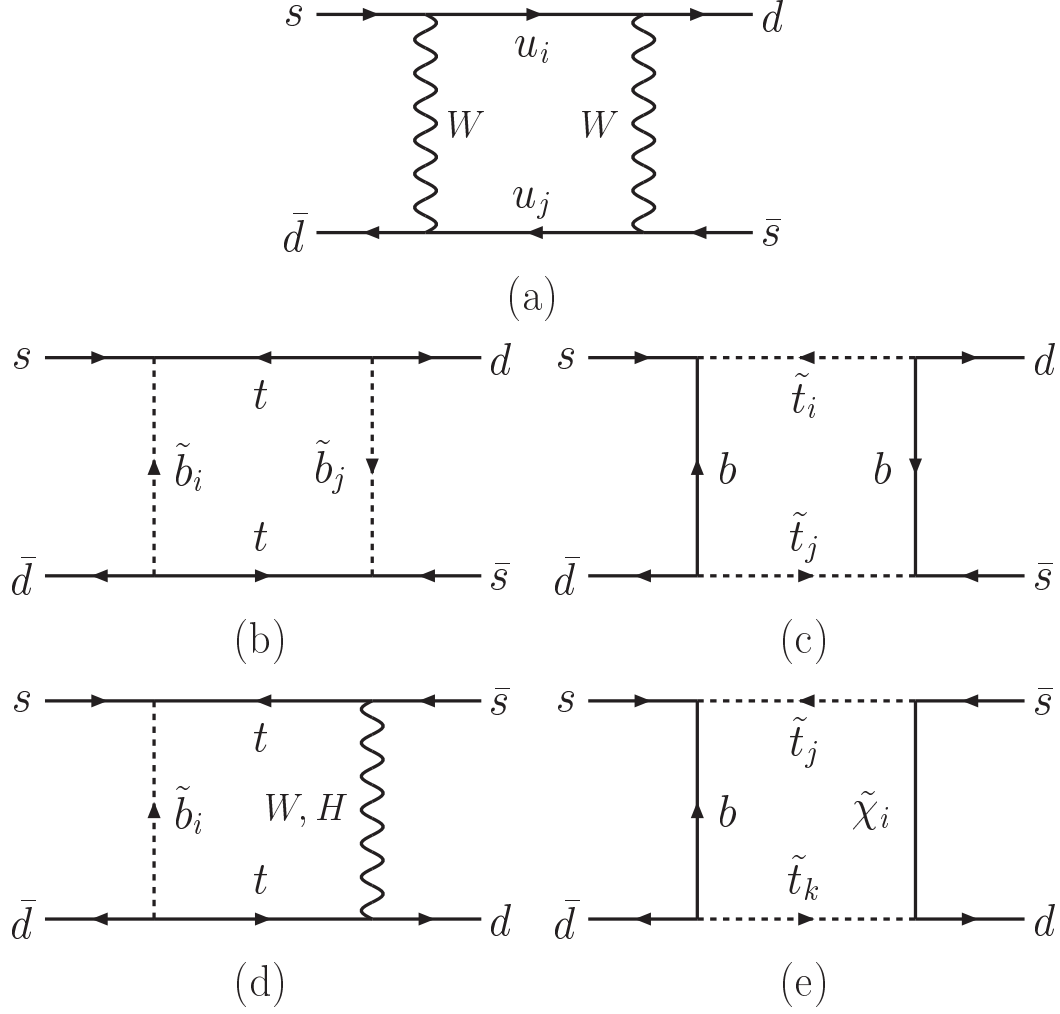


Figure 1: Standard Model diagram (a) and diagrams with R_p -violating couplings (b-e) that give the dominant contributions to $K^0-\bar{K}^0$ mixing. The arrows indicate the flow of baryon number.

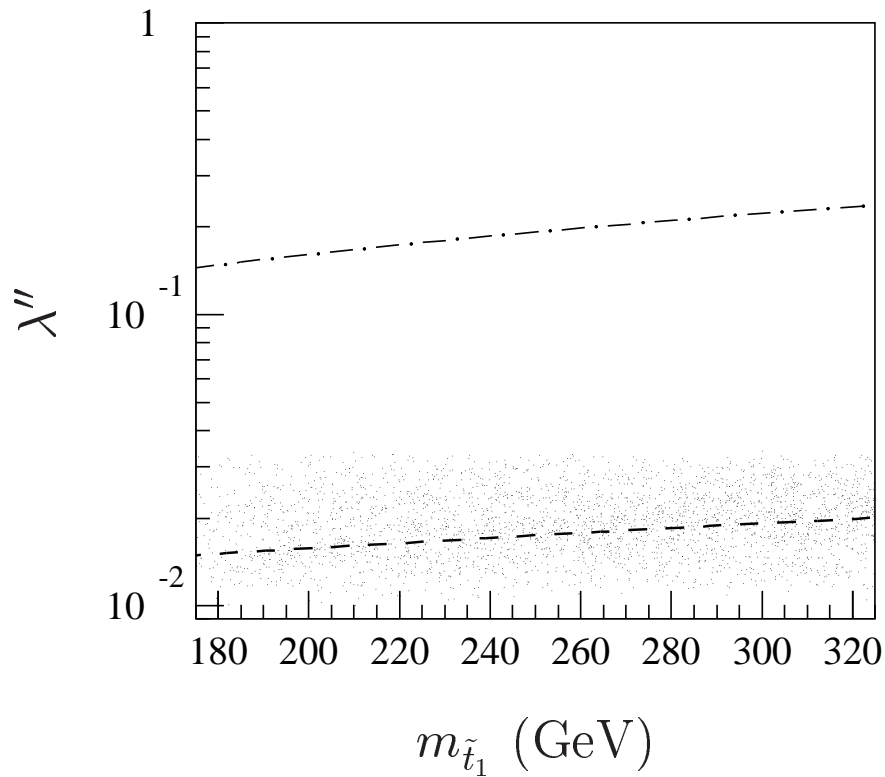


Figure 2: Upper limits on λ'' coming from $K^0-\bar{K}^0$ mixing (dashed line) and B rare decays (dot-dashed line) in the scenario relevant to single stop production, with the choice of parameters considered in [4]. The scattered points are the limits from $K^0-\bar{K}^0$ mixing that result from a wide scan over the MSSM parameter space.

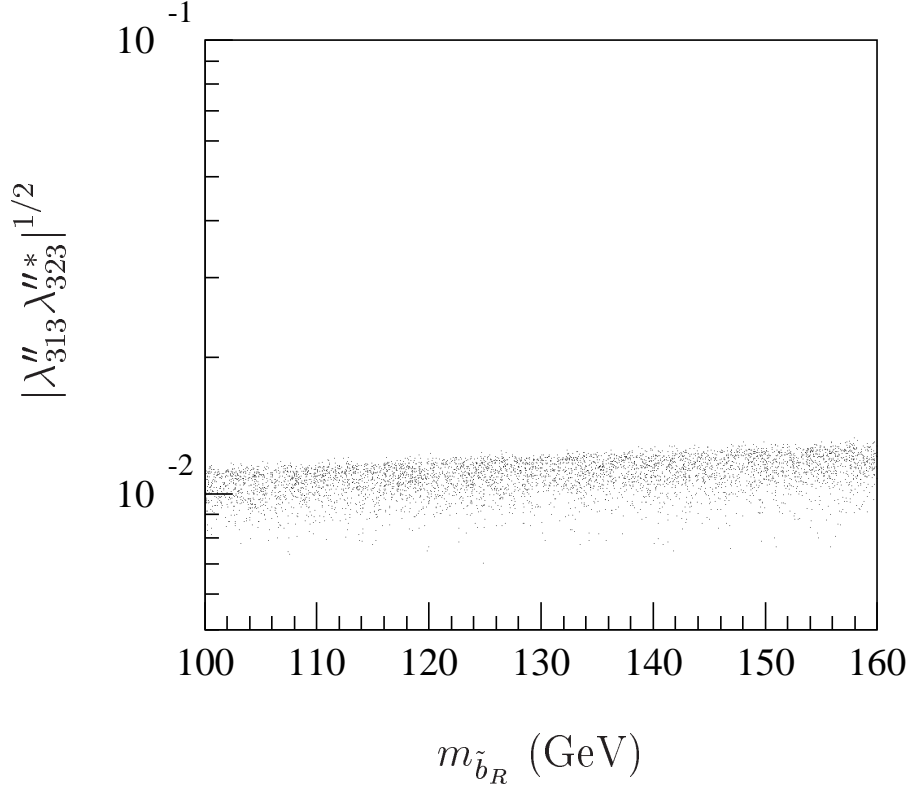


Figure 3: Upper limits on $|\lambda''_{313} \lambda''_{323}|^{1/2}$ coming from $K^0-\bar{K}^0$ mixing, in the scenario relevant to R_p -violating top decays [8]. The scattered points are the limits that result when $M_2 = 100$ GeV, $\tan\beta = 1$, $\mu = -200$ GeV and the other MSSM parameters are varied as described in the text.